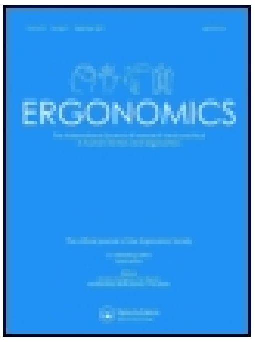

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Impact of joint torques on heel acceleration at heel contact, a contributor to slips and falls

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Slips/falls are a health burden in the workplace. Previous research has implied a relationship between foot dynamics at heel contact and slips/falls; however, heel acceleration has received little attention. Heel acceleration as the heel contacts the ground is the result of the combined effort of the leg joint torques to control motion of the foot. This study aims to examine the association of heel acceleration with fall risk, and explore the main joint torque determinant of heel acceleration at contact. Sixteen young and eleven older adults walked on known dry floors and in slippery environments expected to be dry. Heel acceleration at heel contact in the direction of motion, i.e. anterior/posterior, was compared between slip-recovery and slip-fall outcomes. Results showed that subjects that recovered contacted the floor with a greater heel deceleration ($p < 0.05$) than fall subjects. Knee torque alone explained 76% of the heel acceleration variability ($p < 0.01$). These data suggest that walking with reduced knee flexion torque at heel contact results in a reduced heel deceleration, a potential risk factor for slip-initiated falls.

Keywords: slips; falls; gait; joint torque; heel dynamics

Relevance Statement

Heel acceleration in the direction of motion at heel contact is explored as a potential predictor of slips and falls. Results indicate that walking with a reduced heel deceleration may increase the risk of falling. Heel acceleration may in turn be partially controlled by the knee muscle torque during walking.

1. Introduction

The burden of occupational falls is considerable, particularly in older workers. Falls account for over 20% of work-related deaths and for nearly half of the non-fatal injuries in workers over the age of 65 years old (U.S. Department of Labor – Bureau of Labor Statistics 2005a, U.S. Department of Labor – Bureau of Labor Statistics 2005b). Same-level falls, the most common type of work-related falls especially in older adults, are often initiated by slipping (Layne and Pollack 2004, U.S. Department of Labor – Bureau of Labor Statistics, 2005a). Specifically, answers to the US National Health Interview Survey questionnaire administered in 1997 revealed that 43% of the same-level falls are precipitated by slipping, followed by tripping (18%) and loss of balance (14%)

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(Courtney *et al.* 2001). Injuries attributed to falls can be severe, as more than half of the non-fatal fall-related injuries require emergency department visits (Layne and Pollack 2004) and employees sustaining falls-related injuries often take long sick-leave periods (U.S. Department of Labor – Bureau of Labor Statistics 2005a).

Causes of slip-initiated falls are complex and involve intricate relationships between environmental and human factors (Gronqvist *et al.* 2001a, 2001b, Redfern *et al.* 2001b). Environmental factors include the shoe-floor interface material and frictional properties, which have yet to be reliably evaluated using biofidelic practical measurement devices and testing parameters relevant to human gait (Irvine 1976, Chang *et al.* 2001a, 2001b, 2001c, Gronqvist *et al.* 2003, Beschorner *et al.* 2007). Human factors include neuro-sensorimotor processes (Kim and Robinson 2005, 2006) and higher cognitive mechanisms (Chen *et al.* 1996, Redfern *et al.* 2001a, 2002, Cham and Redfern 2002a, McKenzie and Brown 2004, Brown *et al.* 2006) involved in the detection, perception and anticipation of a perturbation; followed by initiation of appropriate postural responses; and maintenance of dynamic balance. The complex interactions between human and environmental factors contribute to gait biomechanics that are ultimately responsible for failed slip-initiated postural recovery responses and falls.

Gait biomechanics research has identified two broad types of inter-related variables that are likely to have an impact on the risk of slip-initiated falls. The first type of variable is related to postural responses generated after the slip is initiated (Redfern *et al.* 2001b). The body must generate a quick and effective corrective response to re-establish dynamic balance and to maintain an upright posture while continuing with the locomotion task. Lower extremities, trunk and arms all contribute, in a coordinated manner, to the complex postural response generated in an attempt to prevent a fall (Tang and Woollacott 1998, Tang *et al.* 1998, Brady *et al.* 2000, Cham and Redfern 2001, Ferber *et al.* 2002, Marigold and Patla 2002, Marigold *et al.* 2003). Overall, the corrective joint torques generated by the leading/slipping leg, i.e. flexion moment at the knee and hip extension moment, are most consistent and believed to be critical in decelerating the sliding motion of the leading foot and in arresting the vertical descent of the body during a balance loss (Tang *et al.* 1998, Cham and Redfern 2001, Redfern *et al.* 2001b). The second type of variable, often termed initial conditions, refers to gait factors that can be evaluated prior to the initiation of a slip as a result of normal walking patterns. For example, orientation of the foot at heel contact, step length and cadence are initial condition gait factors that have been implicated in slips and falls (Moyer *et al.* 2006, Holbein-Jenny *et al.* 2007). Gait analyses of normal walking patterns can also be used to assess the frictional requirements needed to prevent a slip for a given gait style (Strandberg and Lanshammar 1981, Buczek and Banks 1996, Redfern and DiPasquale 1997, Hanson *et al.* 1999, Burnfield *et al.* 2005, Burnfield and Powers 2006).

Slip events that are most likely to result in a fall occur shortly after contact of the leading foot's heel onto a contaminated floor (Redfern *et al.* 2001b). Thus, it is somewhat intuitive to hypothesise that heel contact dynamics, which are considered initial condition gait variables, may be potential predictors of slips and falls. Studies that have investigated heel contact dynamics as predictors of slips and falls have, to a large extent, focused on heel contact velocity; which is often viewed as a potential risk factor for slipping despite its weak correlation with falls and with the frictional requirement of a slip-resistant gait (Winter *et al.* 1990, Lockhart *et al.* 2003, Winter 2004, Lockhart and Kim 2006).

Little attention has been dedicated to heel acceleration of the leading foot evaluated at heel contact in the direction of motion, i.e. in the anterior/posterior direction. Heel acceleration reflects the combined effects of joint torques generated by the body

(Lockhart and Kim 2006) and it is a determinant of heel velocity shortly after heel contact. Thus, heel acceleration of the leading foot at heel contact may contribute to slip/fall risk. One study from our group reported no statistically significant differences in heel acceleration at heel contact between fallers and non-fallers (Cham and Redfern 2002b). However, in that study, although subjects did not know the specific timing and potential contaminant used to induce the slip, they were exposed to multiple slips. Thus, participants may have modified foot contact kinematics as a result of anticipating a slippery condition (Cham and Redfern 2002a, Heiden *et al.* 2006). Due to the volume of studies considering heel velocity compared to the relatively few studies that have examined heel acceleration, this paper is focused primarily on heel acceleration at heel contact instead of heel velocity at heel contact.

Heel contact dynamics are one example of variables that can be affected by the complex interaction between environmental and human factors. The determinants of heel contact dynamics have not been disentangled. In this study, we hypothesise that the joint torques generated by the leading leg play a significant role in controlling heel acceleration at heel contact. Understanding how humans modulate heel contact dynamics, gait factors that have been implicated in slips and falls, may provide insight into the significant variability in these measures reported among participants in recent investigations (Holbein-Jenny *et al.* 2007).

Thus, the primary goal of this study was to examine the association of the anterior/posterior (direction of motion) heel acceleration of the leading foot evaluated at heel contact to slip outcome (fall or recovery) in young and older adults. The second goal was to investigate the relationship between sagittal-plane joint torques generated by the leading leg (ankle, knee and hip) and the anterior/posterior heel acceleration at heel contact.

2. Methods

2.1. *Subjects, experimental conditions and protocol*

Of a total of 31 recruited participants, 27 subjects were analysed and divided in two age groups, a younger group ($n = 16$ between 20 and 33 years old) and an older group ($n = 11$ between 55 and 67 years old). Four subjects were not analysed due to technical or testing problems. Written informed consent, approved by the University of Pittsburgh Institutional Review Board, was obtained prior to participation. Exclusion criteria included clinically significant conditions that impede normal walking or affect balance as determined by a neurological examination conducted by a neurologist with expertise in balance disorders. No statistically significant differences in stature and gait speed were found between age groups, however older participants were heavier than their younger counterparts ($p < 0.05$) (Table 1).

Table 1. Subject population characteristics stratified by age group.

	Age group (mean (stand. dev.) min–max)	
	Younger	Older
N	16 (10 female, 6 male)	11 (7 female, 4 male)
Age (years)	24 (3.3) 20–33	61 (4.0) 55–67
Stature (cm)	170.2 (8.3) 159.0–194.1	166.2 (8.1) 154.0–179.0
Weight (kg)*	66.8 (10.4) 53.3–89.1	78.2 (10.9) 56.4–92.7

*$p < 0.01$.

Subjects were exposed to two environmental conditions. First, baseline gait trials (known dry environment) were collected. Second, a slip was induced unexpectedly using a diluted glycerol contaminant (75% glycerol/25% water) applied onto the force platform prior to the slip gait trial. The same researcher applied a consistent amount of contaminant to uniformly and completely cover the surface of the force platform used to measure forces under the leading leg. The dynamic coefficient of friction of the shoe–floor interface was 0.53 and 0.03 for the dry and contaminated conditions, respectively, as measured by English XL VIT Slipmeter® (ASTM F1679). The lights were slightly dimmed during the entire experiment to prevent the subject from noticing the glycerol when it was applied onto the floor.

Subjects wore the same brand/model of polyvinyl chloride soled shoes and donned a safety harness. Their body and shoes were instrumented with a set of 79 reflective markers to track gait kinematics at 120 Hz (Moyer 2006). Next, participants were instructed to walk naturally at a self-selected pace and were allowed to practise walking across the 8.5 m long vinyl-tiled walkway. The walkway was instrumented with two force platforms to collect bilateral ground reaction forces at 1080 Hz. Prior to each gait trial, the participant was asked to face away from the walkway and to listen to music for about 1–2 minutes prior to data collection. In addition to the dimmed environment mentioned previously, these procedures were adopted so that glycerol could be applied in the slippery condition without the subject's knowledge. Data collection during the baseline gait trials began after the subject was told that the first few trials would be dry, thus ensuring natural gait and minimising any anticipatory effects. After two or three dry trials, the glycerol was applied to the leading leg force platform without the subject's knowledge and the unexpected slippery gait trial was collected. Only one dry trial (last good trial collected immediately prior to the slippery condition) and the slip trial were considered in the analysis.

2.2. *Data processing*

Heel motion was tracked with a marker placed at the superior posterior aspect of the calcaneous, typically the very back of the heel about 50 mm off the ground. Heel position data in the anterior/posterior direction, i.e. direction of motion, were filtered using a zero-phase second-order Butterworth filter with a cut-off frequency of 10 Hz. From the filtered heel position data, heel velocity and acceleration trajectories were derived using the central difference formula based on three points as shown in Equations (1)–(2) below:

$$HeelVel_i = \frac{HeelPos_{i+1} - HeelPos_{i-1}}{2\Delta t}. \tag{1}$$

$$HeelAcc_i = \frac{HeelPos_{i+1} - 2HeelPos_i + HeelPos_{i-1}}{\Delta t^2}. \tag{2}$$

where $HeelPos_i =$ position of the heel in the anterior-posterior direction at frame i, $HeelVel_i =$ velocity of the heel in the anterior-posterior direction at frame i, $HeelAcc_i =$ acceleration of the heel in the anterior-posterior direction at frame i, and $\Delta t =$ time step of 1/120 s.

At the time of heel contact, *HeelVel* is typically positive (anterior) and *HeelAcc* is typically negative (posterior) meaning that the foot is decelerating (Figure 1). The variable

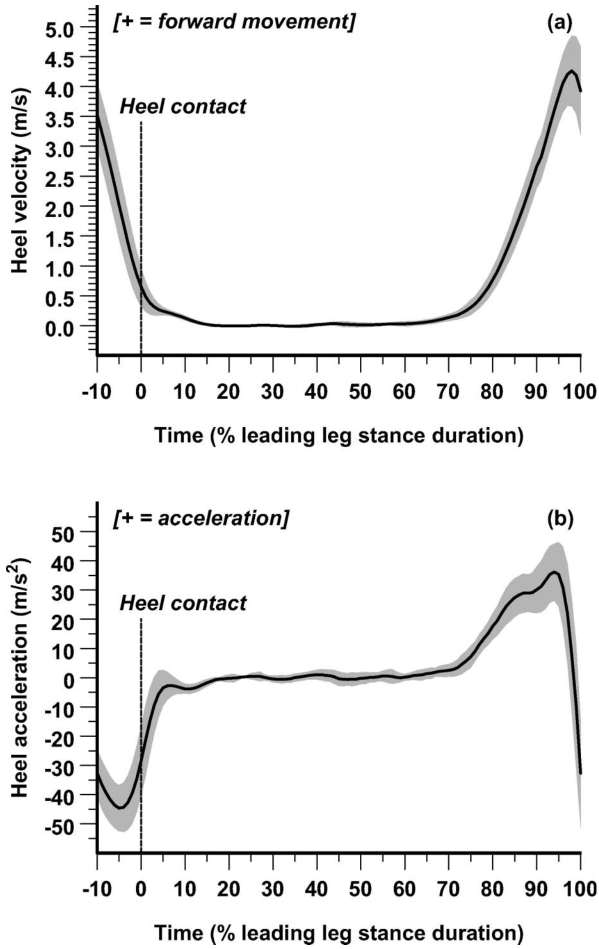

Figure 1. Average (black line) +/−1 standard deviation (grey envelope) of anterior-posterior heel velocity (a) and acceleration (b) time series during baseline (known dry conditions). Time is normalised by stance time; 0% represents heel contact and 100% is toe off. Heel contact was characterised initially by a forward-moving heel with a large heel deceleration (negative heel acceleration) before, at and after heel contact. The foot has nearly stopped by about 5% stance.

HeelAcc, which represents the anterior/posterior heel acceleration, is akin to the variable HeelAccX reported in Cham and Redfern (2002b).

Joint torques were determined using inverse dynamics analyses based on a 15-segment whole-body model developed in our laboratory. This model includes toe, heel, shank, thigh, upper arm, and forearm segments for the right and left sides of the body, as well as pelvis, torso and head segments. Local coordinate systems for each segment were defined using markers from that segment and were, to a considerable extent, based on the work of de Leva (1996) with reasonable effort extended to align local coordinate systems with ISB recommendations especially for the pelvis, thigh, shank and foot segments. Gender-specific segmental masses, centre of mass locations, and radii of gyration were adapted from de Leva (1996). Joint moments are reported in the coordinate system of the more proximal segment. The reader is referred to Moyer (2006) for more details on the model used in the inverse dynamics analyses. For this study, only sagittal-plane joint torques generated by the ankle, knee and hip of the leading leg were evaluated, i.e. *AnklTorq, KneeTorq, HipTorq*, respectively. These torques were normalised by dividing by body mass of the subject. The sign convention for the joint torques is positive for ankle plantarflexion, knee flexion and hip extension.

The timing of heel contact, measured from forceplate data, was chosen to parameterise heel acceleration ($HeelAcc_{HC}$), ankle, knee and hip torques (i.e. $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$, respectively) as it represents the state of these variables prior to the effects of contact forces between the shoe and floor. Both acceleration and joint torque measures were parameterised at the same time (heel contact) based on the rationale from Newton's equations of motions that force and acceleration patterns are instantaneously coupled. While the three-point differentiation method means that one point after heel contact is used in the calculation of heel acceleration and joint torques, shoe–floor forces within this time range are minimal due to the high sampling rate of the cameras (120 Hz) (Figure 2).

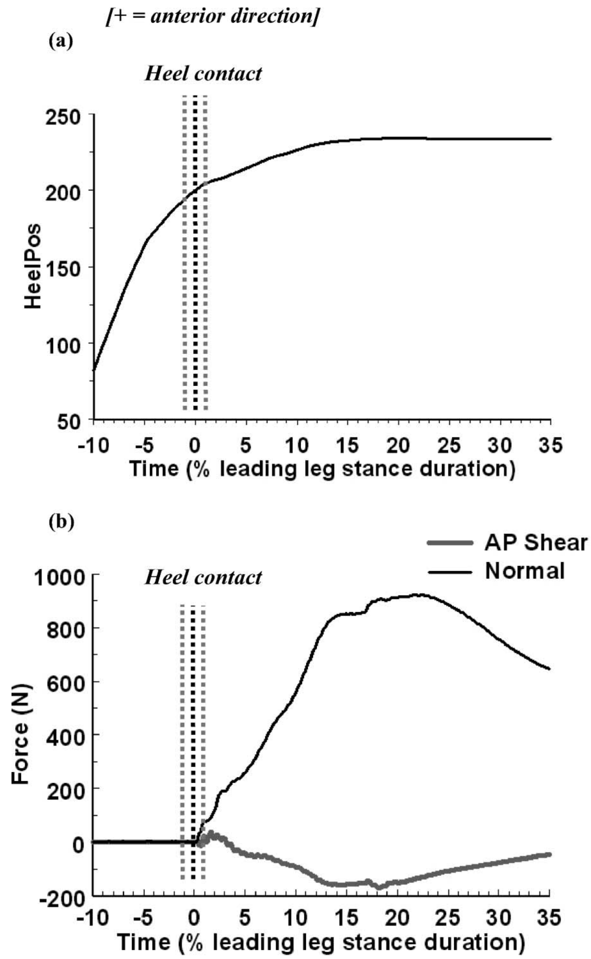

Figure 2. Typical time series of (a) heel position (*HeelPos*) in the anterior/posterior direction, i.e. direction of motion, with positive being forward, and (b) ground reaction forces in the anterior/posterior direction (AP Shear) and normal to the floor (Normal) for a single non-slippery trial. Heel contact is marked by the dashed black line, while the other two time points used in the differentiation are grey vertical lines.

Therefore, at heel contact, heel acceleration and joint moments are not affected by slip reactions and are only minimally affected by shoe–floor interactions (i.e. contact and tribological effects).

The outcome of each slip trial was classified as a fall or recovery. Specifically, a slip trial was classified as a fall if the midpoint between the left and right hip joint centre dropped below 95% of its minimum height measured during normal gait. This fall classification criterion, similar to that of Pai and colleagues (Pai *et al*., 2003, Pavol *et al*. 2002), was also selected in the light of the presumed objective of slip-initiated postural responses observed in our slip-fall experiments: namely to prevent the vertical descent of the body. Finally, this fall classification criterion also agreed with the visual inspection of recorded trials for all obvious falls and identified trials as falls that were otherwise difficult to visually classify as falls or recoveries. Enough slack was left in the harness so that it did not catch subjects before they reached this fall threshold.

Gait speed, cadence and step length normalised to leg length (termed step length ratio) were recorded to characterise the walking style of the subjects. Step length and cadence were calculated using the heel marker and gait velocity was calculated as the average centre of mass velocity. These variables were derived both in the known dry environment and in the contaminated condition prior to slip onset.

3. Results

Heel velocity and acceleration trajectories in the anterior-posterior direction (*HeelVel* and *HeelAcc*, respectively) during the dry conditions were consistent across subjects, as reflected by the relatively small standard deviation magnitude (Figure 1). The horizontal heel dynamics are characterised by a rapid deceleration before, at, and soon after heel contact bringing the foot nearly to a stop by about 5% of stance time. The heel does not start to move again until later in the stance as the subject prepares for the unloading/swing phase. Joint torque trajectories were found to be similar to previously published results (Cham and Redfern 2001, 2002a). In particular, at heel contact, the ankle, knee and hip joints of the leading leg generate a plantarflexion, flexion and extension torque, respectively. Specifically, the mean (standard deviation) values for $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$ were 0.12 (0.05), 0.37 (0.09) and 0.47 (0.17) $N \cdot m/kg$, respectively. No age group differences in joint torques at heel contact were found ($p > 0.05$).

There were no significant within-subject differences in gait speed, step length ratio, cadence, heel dynamics ($HeelAcc_{HC}$) or joint torques ($AnklTorq_{HC}$, $KneeTorq_{HC}$, $HipTorq_{HC}$) between baseline and slippery conditions ($p > 0.05$). These findings imply that subjects did not anticipate the slippery floor during the contaminated conditions and that shoe-floor interaction minimally affected the measured parameters. Thus, within-subject means of these variables were computed across conditions and used in subsequent analyses.

3.1. Overview of general gait differences between recoveries and falls

The slip outcome classification yielded 10 falls and 17 recoveries (Table 2). Subjects classified as falls slipped with a greater anterior heel velocity and acceleration throughout the slip (Figure 3). Overall, older subjects experienced a slightly greater rate of falls than younger participants, specifically 45% (5 out of 11) versus 31% (5 out of 16). Statistical analyses regressing general gait variables of interest on *age group, slip outcome* and *age group* $\times$ *slip outcome* revealed significant differences only in cadence between recoveries

Table 2. General gait characteristics stratified by slip outcome and age group.

Slip outcome:	Fall		Recovery	
Age group:	Older	Younger	Older	Younger
n (% fall/recovery events within age group)	5 (45%)	5 (31%)	6 (55%)	11 (69%)
Required coefficient of friction	0.21 (0.05)	0.19 (0.02)	0.19 (0.02)	0.20 (0.02)
Gait speed (m/s)	1.4 (0.1)	1.4 (0.1)	1.4 (0.1)	1.5 (0.1)
Step length ratio ($p_{\text{age}} < 0.05$)	0.79 (0.04)	0.84 (0.02)	0.77 (0.06)	0.83 (0.07)
Cadence (steps/min) ($p_{\text{outcome}} < 0.01$)	115 (9)	109 (9)	126 (10)	120 (8)

Continuous gait variables of interest were each regressed on *slip outcome, age group*, and *slip outcome* × *age group*. Statistically significant effects are indicated in brackets in the first column.

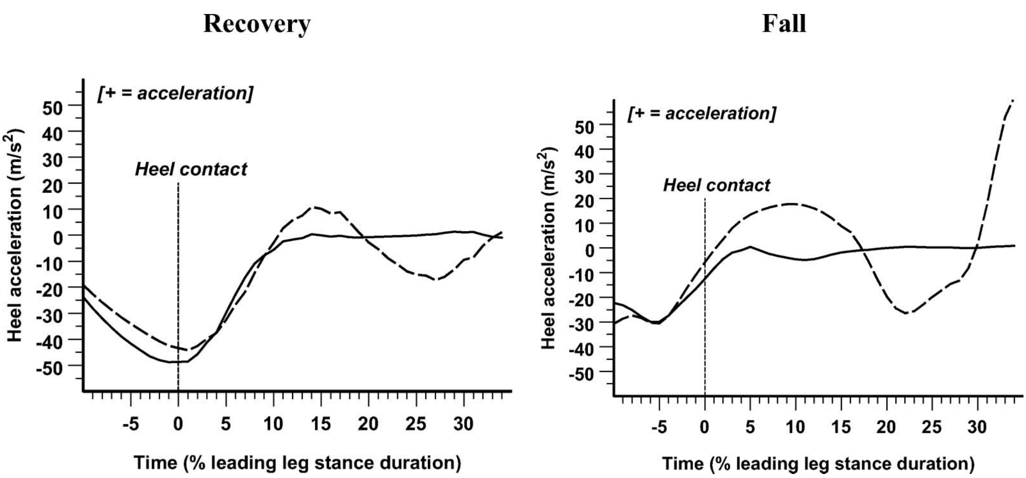

Figure 3. Typical time series plots for anterior-posterior acceleration from two subjects, one who recovered and one who fell in the slippery condition. Data collected in the slippery condition (dashed line) and baseline trial (solid line) are represented for the same two subjects. Heel contact occurs at time 0. The recovery subject contacted the floor with a greater heel deceleration compared to the subject who fell.

and falls (Table 2). Specifically, a faster cadence characterised the gait patterns of subjects who recovered from the slip compared to participants who fell ($p < 0.05$, Table 2). Only age-group differences in step length ratio were statistically significant, with older adults taking shorter steps than their younger counterparts ($p < 0.05$, Table 2). Gait speed was similar between age groups and slip outcomes, i.e. about 1.4 m/s ($p > 0.1$, Table 2).

3.2. *Contribution of heel acceleration at heel contact to slip outcome*

To test differences in heel contact dynamics between slip outcomes in young and older participants, a regression analysis was conducted with *age group, slip outcome* and their interaction used as predictors and with $HeelAcc_{HC}$ as the dependent variable. This analysis revealed that subjects who recovered had a greater heel deceleration (greater negative acceleration) at heel contact than subjects who fell (Figure 4, $p < 0.05$). The regression analyses reflected no statistically significant *age group* and *slip outcome* × *age group* effects.

3.3. *Heel contact heel acceleration determined by joint torques*

All three joint torques at heel contact were found to strongly correlate with heel acceleration at heel contact ($|r| \sim 0.6$–0.9, Table 3). Specifically, increasing ankle plantarflexion, knee flexion and hip extension moment resulted in greater heel deceleration (negative acceleration) at heel contact ($p < 0.01$). As ankle, knee and hip torques are interdependent, as shown by the Pearson correlation coefficients (Table 3), further regression analyses were conducted to determine the main joint contributor to heel acceleration at heel contact. Specifically, $HeelAcc_{HC}$ was regressed on $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$ both individually and simultaneously in different models and the behaviour of model R^2 was examined (Table 4). In order to determine driving determinants of heel contact heel acceleration, special attention was paid to the additional contribution of a specific joint torque to explaining $HeelAcc_{HC}$ variability above and beyond that explained by other joint torques (reflected by ΔR^2 between models in Table 4). Findings of this analysis indicate that a greater proportion of the variability in $HeelAcc_{HC}$ is explained by knee torque than by ankle or hip torques (Table 4).

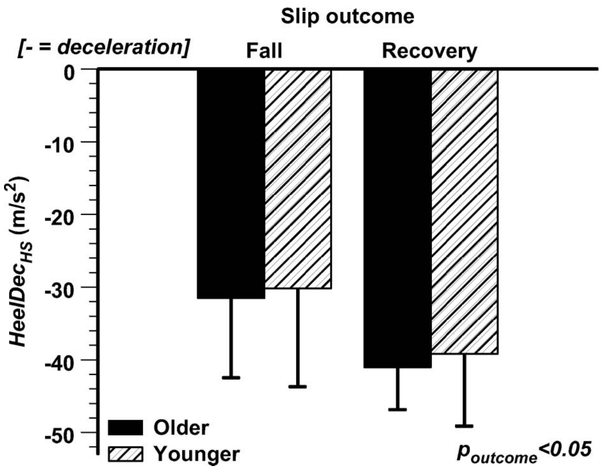

Figure 4. Average heel acceleration at heel contact stratified by slip outcome in older and younger participants. Subjects who recovered from the slip walked with a greater $HeelAcc_{HC}$ value than fallers ($p < 0.05$), indicating that while their heel was moving faster; it was decelerating at a larger rate. Error bars reflect standard deviations.

Table 3. Pearson correlation coefficients relating gait variables of interest.

$HeelAcc_{HC}$	−0.48*	0.09	−0.62**	−0.62**	−0.87**	−0.75**
	Gait speed	0.31	0.65**	0.27	0.52**	0.55**
		Step length ratio	−0.15	0.11	−0.10	−0.25
			Cadence	−0.02	0.53**	0.81**
				$AnklTorq_{HC}$	0.72**	0.32
					$KneeTorq_{HC}$	0.83**
						$HipTorq_{HC}$

Significant correlation (*$p < 0.05$, **$p < 0.01$). $HeelAcc_{HC}$, acceleration of the heel evaluated at heel contact in the anterior/posterior direction; step length ratio: step length normalised to leg length; $AnklTorq_{HC}$, ankle plantarflexion torque at heel contact; $KneeTorq_{HC}$, knee flexion torque at heel contact; $HipTorq_{HC}$, hip extension torque at heel contact.

Table 4. R^2 values obtained by regressing $HeelAcc_{HC}$ on each joint torque individually and simultaneously.

Independent variables	Model 1 $AnklTorq_{HC}$	Model 2 $KneeTorq_{HC}$	Model 3 $HipTorq_{HC}$	Model 4 $AnklTorq_{HC}$ and $KneeTorq_{HC}$	Model 5 $AnklTorq_{HC}$ and $HipTorq_{HC}$	Model 6 $KneeTorq_{HC}$ and $HipTorq_{HC}$	Model 7 $AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$
	0.38	0.76	0.56	0.76	0.72	0.77	0.77
Statistically significant effects							
$AnklTorq_{HC}$	$p < 0.001$	N/A	N/A	$p = 0.863$	$p < 0.002$	N/A	$p = 0.881$
$KneeTorq_{HC}$	N/A	$p < 0.001$	N/A	$p < 0.001$	N/A	$p < 0.001$	$p = 0.054$
$HipTorq_{HC}$	N/A	N/A	$p < 0.001$	N/A	$p < 0.001$	$p = 0.694$	$p = 0.707$

ΔR^2 between models can be computed *to gain a better understanding of independent joint torque contributions to explaining the variability in heel contact heel acceleration*. For example, ΔR^2 between Model 7 and Model 2 indicates that adding ankle and hip torque in the regression model explains only 1% of the variability in $HeelAcc_{HC}$ above and beyond contributions made by the knee torque.

For example, 76% of the variability in $HeelAcc_{HC}$ is explained by $KneeTorq_{HC}$ alone, compared to 38 and 56% by $AnklTorq_{HC}$ and $HipTorq_{HC}$ alone, respectively. Furthermore, the added contribution to R^2 by the combination of any two or all three joint torques explained no more than 1% of the variability in $HeelAcc_{HC}$ above and beyond the contribution by $KneeTorq_{HC}$ alone. In summary, knee kinetics are the main determinant of heel acceleration at heel contact, with increasing knee flexion torque being positively correlated with heel contact heel deceleration (Figure 5, $p < 0.01$).

3.4. Relationship between heel acceleration at heel contact and general gait variables

A multivariate regression analysis was performed among $HeelAcc_{HC}$, joint torques at heel contact ($AnklTorq_{HC}$, $KneeTorq_{HC}$ and $HipTorq_{HC}$) and spatiotemporal gait variables to gain a general understanding of the relationship among all of these variables (Table 3). $HeelAcc_{HC}$ was found to significantly correlate with gait speed and cadence: specifically a higher gait speed and cadence were correlated with more negative $HeelAcc_{HC}$ (higher heel deceleration). Some interrelation between joint torques was found: $AnklTorq_{HC}$ was positively correlated with $KneeTorq_{HC}$ and $KneeTorq_{HC}$ was positively correlated with $HipTorq_{HC}$. In addition, $KneeTorq_{HC}$ and $HipTorq_{HC}$ were both positively correlated with cadence and gait speed. Step length ratio was not correlated with any other variable measured.

4. Discussion

Anterior heel acceleration at heel contact was found to be a significant contributor to slip outcome. Specifically, greater deceleration (negative acceleration) at heel contact was associated with an improved chance of slip recovery. Additionally, knee flexion torque of the leading leg appears to be the major determinant of heel acceleration at heel contact. Heel acceleration at heel contact correlates with gait variables previously identified as potential contributors to hazardous slips, e.g. cadence. Finally, no statistically significant age group effects were found.

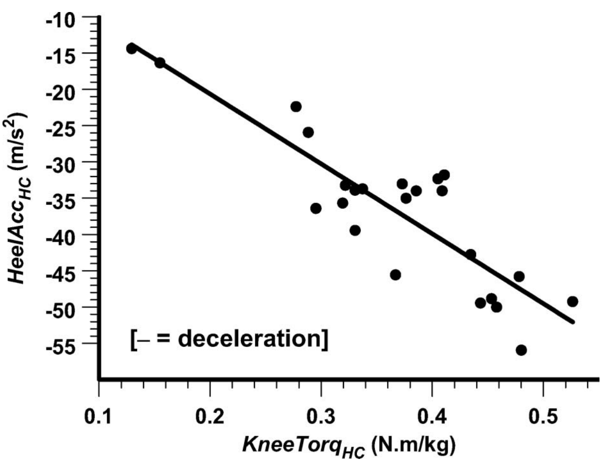

Figure 5. Heel deceleration (negative acceleration) at heel contact increases with knee flexion torque.

Findings of this study suggest that leading leg kinetics at heel contact, particularly knee flexion torque coupled with hip extension torque, play a significant role in reducing the risk of slips and falls by increasing heel acceleration. Although leg kinetics have not been previously linked with heel dynamics, the beneficial effects of increased knee flexion and hip extension torques have been reported in studies examining both reactive and proactive slip-related responses. Indeed, once a slip is initiated, reactive strategies consist of increasing knee flexion and hip extension torques in an attempt to slow the slipping leg down and to move the centre of mass over the leading leg (Cham and Redfern, 2001). Similarly, proactive strategies, often generated when anticipating a slip, also consist of increased hip extensor and knee flexor muscle activity, particularly in muscles such as the biceps femoris (Tang *et al.* 1998) and medial hamstring (Chambers and Cham 2007). Therefore healthy subjects anticipating a slip, and thus presumably adopting a safer walking style, are shown to further activate muscles that generate joint torques found in this study to correlate with heel acceleration. In summary, having greater knee flexion and hip extension torques occurring naturally in the gait cycle especially at heel contact may be important in successfully decelerating the heel, decreasing the extent of the individual's reliance on shoe–floor friction or reactive responses to recover balance, and can potentially be perceived as a safer walking pattern.

The importance of heel acceleration at heel contact may contribute to the lack of consistent evidence in studies that investigated associations between heel velocity and fall risk. For example, Lockhart *et al.* (2003) associated a higher fall rate among older adults with an increased heel velocity at heel contact, while Lockhart and Kim (2006) found that older adults, who also fell at a higher rate than their young counter parts, had a smaller heel velocity at heel contact. Heel acceleration at heel contact, a result of leading leg joint torques, rapidly decreases heel velocity shortly after heel contact. The combined effect of heel velocity and acceleration at heel contact may explain a greater proportion of the variability in initial conditions of the heel and subsequently fall risk than heel velocity alone. Intuitively, subjects with higher anterior heel velocity at heel contact can compensate with increased heel deceleration (rearward acceleration) at heel contact.

The findings correlating heel acceleration at heel contact with slip outcome may be of particular interest in identifying individuals at greater risk of slipping and falling. Heel acceleration at heel contact can be easily and inexpensively measured with accelerometers and pressure sensors or footswitches to determine the timing of heel contact. In fact, quality of data acquired with accelerometers may be improved beyond this study because accelerometers do not require data to be twice differentiated when acquiring acceleration from marker data. Additionally, this research has shown that heel acceleration at heel contact is correlated with cadence. Specifically, increasing cadence may be one way to increase heel contact heel deceleration. More research is needed to determine whether imposing changes in cadence actually affects heel contact heel dynamics and whether this change will lead to improved slip/fall risk. While heel acceleration reflects the kinetics of the leading leg at heel contact, it is not completely deterministic of the outcome of a slip as post-slip reactions also play a vital role in determining the outcome of a slip (Iqbal and Pai 2000, Cham and Redfern 2001, Redfern *et al.* 2001, Marigold and Patla 2002).

No age-group effects were found. These findings imply that the older adults in this study had relationships between heel dynamics and slip risk/outcome similar to those of the younger adults. These results may be due to the fact that our group of older participants was very healthy (rigorous screening) and perhaps not old enough to reflect age-group differences. Older adults over the age of 70 years were not enrolled in this study due to safety constraints related to the slippery conditions included in the protocol. Thus, age and health characteristics of the subjects used in this study may have somewhat restricted the implication of the findings in other populations. For example, in frail older adults, particularly those with deficiencies in lower leg strength, the relationships between heel acceleration, joint torques and fall risk may be different from the results reported in this study.

In conclusion, a reduced deceleration of the heel at heel contact may be a risk factor for slip-initiated falls. The torque generated by the knee of the leading leg is a significant determinant of heel contact heel acceleration. While an intervention study is needed to determine the effectivity of manipulating heel acceleration to reduce fall risk, the results of this research are promising for identification and improvement of high-risk walking styles.

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References

ASTM F-1679–04, 2006. Standard test method for using a variable incidence tribometer (VIT). *Annual Book of ASTM Standards 15.07*. West Conshohocken, PA: ASTM.

Beschorner, K.E., Redfern, M.S., Porter, W.L., and Debski, R.E., 2007. Effects of slip testing parameters on measured coefficient of friction. *Applied Ergonomics*, 38, 773–780.

Brady, R.A., Pavol, M.J., Owings, T.M., and Grabiner, M.D., 2000. Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. *Journal of Biomechanics*, 33, 803–808.

Brown, L.A., Doan, J.B., McKenzie, N.C., and Cooper, S.A., 2006. Anxiety-mediated gait adaptations reduce errors of obstacle negotiation among younger and older adults: Implications for fall risk. *Gait and Posture*, 24, 418–423.

Buczek, F.L. and Banks, S.A., 1996. High-resolution force plate analysis of utilized slip resistance in human walking. *Journal of Testing and Evaluation*, 24, 353–358.

Burnfield, J.M. and Powers, C.M., 2006. Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. *Ergonomics*, 49, 982–995.

Burnfield, J.M., Tsai, Y.J., and Powers, C.M., 2005. Comparison of utilized coefficient of friction during different walking tasks in persons with and without a disability. *Gait and Posture*, 22, 82–88.

Cham, R. and Redfern, M.S., 2001. Lower extremity corrective reactions to slip events. *Journal of Biomechanics*, 34, 1439–1445.

Cham, R. and Redfern, M.S., 2002a. Changes in gait when anticipating slippery floors. *Gait and Posture*, 15, 159–171.

Cham, R. and Redfern, M.S., 2002b. Heel contact dynamics during slip events on level and inclined surfaces. *Safety Science*, 40, 559–756.

Chambers, A.J. and Cham, R., 2007. Slip-related muscle activation patterns in the stance leg during walking. *Gait and Posture*, 25, 565–572.

Chang, W.-R., Grönqvist, R., Leclercq, S., Brungraber, R.J., Mattke, U., Strandberg, L., Thorpe, S., Myung, R., Makkonen, L. and Courtney, L., 2001a. The role of friction in the measurement of slipperiness, Part 2: survey of friction measurement devices. *Ergonomics*, 44, 1233–1261.

Chang, W.-R., Grönqvist, R., Leclercq, S., Myung, R., Makkonen, L., Strandberg, L., Brungraber, R.J., Mattke, U., and Thorpe, S., 2001b. The role of friction in the measurement of slipperiness, Part 1: friction mechanisms and definition of test conditions. *Ergonomics*, 44, 1217–1232.

Chang, W.-R., Kim, I., Manning, D.P., and Bunterngchit, Y., 2001c. The role of surface roughness in the measurement of slipperiness. *Ergonomics*, 44, 1200–1216.

Chen, H.C., Schultz, A.B., Ashton-Miller, J.A., Giordani, B., Alexander, N.B., and Guire, K.E., 1996. Stepping over obstacles: dividing attention impairs performance of old more than young adults. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 51, M116–M122.

Courtney, T.K., Sorock, G.S., Manning, D.P., and Holbein, M.A., 2001. Occupational slip, trip, and fall-related injuries–can the contribution of slipperiness be isolated? *Ergonomics*, 44, 1118–1137.

deLeva, P., 1996. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, 29, 1223–1230.

Ferber, R., Osternig, L.R., Woollacott, M.H., Wasielewski, N.J., and Lee, J.H., 2002. Reactive balance adjustments to unexpected perturbations during human walking. *Gait and Posture*, 16, 238–248.

Gronqvist, R., Abeysekera, J., Gard, G., Hsiang, S.M., Leamon, T.B., Newman, D.J., Gielo-Perczak, K., Lockhart, T.E., and Pai, C.Y., 2001a. Human-centred approaches in slipperiness measurement. *Ergonomics*, 44, 1167–1199.

Grönqvist, R., Chang, W.-R., Courtney, T.K., Leamon, T.B., Redfern, M.S., and Strandberg, L., 2001b. Measurement of slipperiness: fundamental concepts and definitions. *Ergonomics*, 44, 1102–1117.

Gronqvist, R., Hirvonen, M., Rajamaki, E., and Matz, S., 2003. The validity and reliability of a portable slip meter for determining floor slipperiness during simulated heel strike. *Accident Analysis and Prevention*, 35, 211–225.

Hanson, J.P., Redfern, M.S., and Mazumdar, M., 1999. Predicting slips and falls considering required and available friction. *Ergonomics*, 42, 1619–1633.

Heiden, T.L., Sanderson, D.J., Inglis, J.T., and Siegmund, G.P., 2006. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. *Gait and Posture*, 24, 237–246.

Holbein-Jenny, M.A., Redfern, M.S., Gottesman, D., and Chaffin, D.B., 2007. Kinematics of heelstrike during walking and carrying: implications for slip resistance testing. *Ergonomics*, 50, 352–363.

Irvine, C.H., 1976. Evaluation of some factors affecting measurements of slip resistance of shoe sole materials on floor surfaces. *Journal of Testing and Evaluation*, 4, 133–138.

Iqbal, K. and Pai, Y., 2000. Predicted region of stability for balance recovery: motion at the knee joint can improve termination of forward movement. *J Biomech*, 33, 1619–1627.

Kim, B.J. and Robinson, C.J., 2005. Postural control and detection of slip/fall initiation in the elderly population. *Ergonomics*, 48, 1065–1085.

Kim, B.J. and Robinson, C.J., 2006. Effects of diabetic neuropathy on body sway and slip perturbation detection in older population. *Int J Occup Saf Ergon*, 12, 241–254.

Layne, L.A. and Pollack, K.M., 2004. Nonfatal occupational injuries from slips, trips, and falls among older workers treated in hospital emergency departments, United States 1998. *American Journal of Industrial Medicine*, 46, 32–41.

Lockhart, T.E. and Kim, S., 2006. Relationship between hamstring activation rate and heel contact velocity: factors influencing age-related slip-induced falls. *Gait and Posture*, 24, 23–34.

Lockhart, T.E., Woldstad, J.C., and Smith, J.L., 2003. Effects of age-related gait changes on the biomechanics of slips and falls. *Ergonomics*, 46, 1136–1160.

Marigold, D.S., Bethune, A.J., and Patla, A.E., 2003. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *Journal of Neurophysiology*, 89, 1727–1737.

Marigold, D.S. and Patla, A.E., 2002. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. *Journal of Neurophysiology*, 88, 339–353.

McKenzie, N.C. and Brown, L.A., 2004. Obstacle negotiation kinematics: age-dependent effects of postural threat. *Gait and Posture*, 19, 226–234.

Moyer, B.E., 2006. *Slip and fall risks: Pre-slip gait contributions and post-slip response effects*. Ph.D. Thesis, University of Pittsburgh.

Moyer, B.E., Chambers, A.J., Redfern, M.S., and Cham, R., 2006. Gait parameters as predictors of slip severity in younger and older adults. *Ergonomics*, 49, 329–343.

Pai, Y.C., 2003. Movement termination and stability in standing. *Exercise and Sports Sciences Reviews*, 31, 19–25.

Pavol, M.J. and Pai, Y.C., 2002. Feedforward adaptations are used to compensate for a potential loss of balance. *Experimental Brain Research*, 145, 528–538.

Redfern, M.S. and DiPasquale, J., 1997. Biomechanics of descending ramps. *Gait and Posture*, 6, 119–125.

Redfern, M.S., Jennings, J.R., Martin, C., and Furman, J.M., 2001a. Attention influences sensory integration for postural control in older adults. *Gait and Posture*, 14, 211–216.

Redfern, M.S., Cham, R., Gielo-Perczak, K., Grönqvist, R., Hirvonen, M., Lanshammar, H., Marpet, M.I., and Pai, Y.C., 2001b. Biomechanics of slips. *Ergonomics*, 44, 1138–1166.

Redfern, M.S., Műller, M.L.T.M., Jennings, R., and Furman, J.M., 2002. Attentional dynamics in postural control during perturbations in young and older adults. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 57A, b298–b303.

Strandberg, L. and Lanshammar, H., 1981. The dynamics of slipping accidents. *Journal of Occupational Accidents*, 3, 153–162.

Tang, P.-F. and Woollacott, M.H., 1998. Inefficient postural responses to unexpected slips during walking in older adults. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 53, M471–M480.

Tang, P.-F., Woollacott, M.H., and Chong, R.K., 1998. Control of reactive balance adjustments in perturbed human walking: roles of proximal and distal postural muscle activity. *Experimental Brain Research*, 119, 141–152.

U.S. Department of Labor – Bureau of Labor Statistics, 2005a. *Lost-worktime injuries and illnesses: characteristics and resulting time away from work, 2004/Supplemental tables*. Washington, DC.

U.S. Department of Labor – Bureau of Labor Statistics, 2005b. *National census of fatal occupational injuries in 2004*. Washington, DC.

Winter, D.A., Patla, A.E., Frank, J.S., and Walt, S.E., 1990. Biomechanical walking pattern changes in the fit and healthy elderly. *Physical Therapy*, 70, 340–347.

Winter, D.A., 2004. *Biomechanics and motor control of human movement*. New York: John Wiley.